

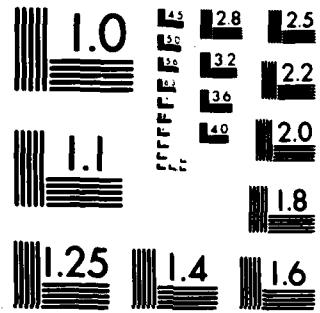
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CARBIDE FORMATION AND FRACTURE
OF
HIGH CARBON STEEL

FINAL REPORT

February 13, 1984

U.S. ARMY RESEARCH OFFICE

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Colorado School of Mines
Golden, Colorado 80401

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number) High carbon steel, bearing steel, martensite, fracture, fracture toughness, carbide formation, intercritical austenitizing, quenching, tempering, intergranular fracture, transgranular fracture.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) <p>This report briefly summarizes the research performed to characterize the fracture of hardened high carbon steels and the formation of carbides during the austenitizing, quenching, and tempering stages of the hardening heat treatments applied to high carbon steels. Four fracture mechanisms and morphologies, each associated with a different type of carbide distribution, were observed and correlated to fracture toughness. Details (over)</p>		

20.

of the findings are presented in the twelve (12) publications resulting from this research.



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A. Statement of the Problem

Many critical tool, machine and bearing applications require the high hardness and resistance to fatigue and wear which high carbon martensitic microstructures tempered at low temperatures provide. Steels which contain such microstructures may be uniformly of high carbon content and through hardened, or carburized so that only the surface or case of the steel develops the high hardness associated with high carbon content after heat treatment. However, despite the beneficial properties associated with high carbon martensite, toughness and fracture resistance are generally quite low and may vary significantly as a function of heat treatment in a given steel.

At the start of the investigation summarized in this report, it was known that several different fracture morphologies could be developed during overload of high carbon steels. Intergranular fracture was related to steels austenitized above A_{cm} and transgranular fracture was related to steels intercritically austenitized between A_1 and A_{cm} .

Many questions remained, however, with respect to the mechanisms of fracture and their relationship to the various microstructural components of a hardened high carbon steel. Also, questions remained about the characterization and formation of carbide during the austenitizing, quenching and tempering stages of a hardening heat treatment.

The above concerns constituted the basis for the major problems, i.e., carbide formation and the effect of carbides on fracture of high carbon steels, studied in the ARO research supported under contract No. DAAG29-81-K-0030 in the period January 1981 through November 19, 1983.

B. Summary of Important Results

The major results of the ARO-supported research in the period 1981 through 1983 fall into two categories. One category includes the results obtained concerning the understanding of carbide formation and characterization in high carbon hardened steels. The other category includes results which characterize fracture and relate the fracture behavior to the various microstructural components of hardened high carbon steel.

The most important results in each of the two categories are summarized in the following two sections. References which document the results are referred to by their numbers in the list of publications which resulted from this ARO-supported research, Section C.

B.1. Carbide Formation and Characterization

Unique carbide distributions form during each stage (austenitizing, quenching, and tempering) of the hardening heat treatments applied to high carbon steels. During austenitizing, if specimens are cooled from above A_{cm} , carbides nucleate and grow on the austenite grain boundaries. In steels containing strong carbide formers, for example AISI 52100 steel which contains nominally 1.5 pct. Cr, Ando and Krauss (C.1, C.2) experimentally followed the initially very rapid and subsequent very sluggish growth of cementite allotriomorph growth. This behavior was explained (C.5, C.8, C.10) by theoretical modeling and experimental evaluation of the growth kinetics of cementite allotriomorphs in high purity Fe-Cr-C alloys. It was found that three stages of growth develop: 1) a very rapid stage dependent only on carbon diffusion where the carbon diffusion fields do not overlap, 2) a second, somewhat slower stage dependent on carbon diffusion where the diffusion fields supplying carbon to the growing allotriomorphs overlap, and 3) a third very sluggish stage dependent on the diffusion of chromium. Moreover, phosphorus was found to accelerate cementite grain boundary allotriomorph formation (C.2) to the degree that very fine cementite particles could form on austenite grain boundaries during quenching. The latter result accounts for the large amount of intergranular fracture that develops in high carbon steels quenched from above A_{cm} (C.3).

On tempering, Ma et al (C.9) showed that chi-carbide rather than cementite formed during the classical third stage of tempering. Three morphologies of the chi-carbide were observed and related to tempered martensite embrittlement. These findings were reported and published in the Peter G. Winchell Symposium on the Tempering of Steel (Metallurgical Transactions A, June 1983, Volume 14A), a symposium for which the principal investigator served as organizer and co-chairman. This symposium was the first major review of tempering phenomena in steels in the last decade.

B.2. Fracture Behavior of High Carbon Hardened Steels

As a result of this research four different fracture morphologies have now been positively identified in hardened high carbon steels (C.3, C.6, C.7, C.11). All of the fracture morphologies are associated with a unique distribution of carbides. There is the transgranular morphology, often associated with low fracture toughness, which develops by microvoid coalescence of the closely spaced spherical carbide particles retained after intercritical austenitizing. If intercritical austenitizing produces a coarser distribution of spherical particles along austenite grain boundaries, an

intergranular mode of fracture with good toughness develops along the network of spherical carbides. Retention of coarse carbide allotriomorph networks from earlier thermomechanical processing produces a pseudo intergranular mode of fracture which may or may not have high toughness depending on the continuity of the carbide network. Finally, specimens austenitized above A_{cm} fracture in an intergranular mode because of fine carbides formed on quenching. The latter fracture mode is exacerbated by phosphorus segregation to austenite grain boundaries and carbide interfaces.

The results of the fracture studies have been presented in invited review papers at the symposium Microstructural and Residual Stress Effects on the Properties of Case Hardened Steels, Atlanta, Georgia, March 1983 and at the Third International Congress on the Heat Treatment of Materials, Shanghai, People's Republic of China, November 1983.

C. List of Publications and Technical Reports

1. T. Ando and G. Krauss: "The Isothermal Thickening of Cementite Allotriomorphs in a 1.5Cr-1C Steel," *Acta Metallurgica*, Vol. 29, 1981, pp. 351-363.
2. T. Ando and G. Krauss: "The Effect of Phosphorus Content on Grain Boundary Cementite Formation in AISI 52100 Steel," *Metallurgical Transactions A*, Vol. 12A, 1981, pp. 1283-1290.
3. D. L. Yaney: "The Effects of Phosphorus and Tempering on the Fracture of AISI 52100 Steel," M.S. Thesis, Colorado School of Mines, Golden, Colorado, 80401.
4. G. Krauss: "The Effect of Austenitizing on Microstructure and Fracture of Hardened High Carbon Steels," in Wear and Fracture Prevention, ASM, 1981, pp. 147-161.
5. T. Ando: "Isothermal Growth of Grain Boundary Allotriomorphs of Cementite in Ternary Fe-C-Cr Austenite," Doctoral Dissertation, Colorado School of Mines, 1982.
6. F. S. Shen and G. Krauss: "The Effect of Phosphorus Content and Proeutectoid Carbide Distribution of the Fracture Behavior of 52100 Steel," *Journal of Heat Treating*, Vol. 2, 1982, pp. 238-249.
7. G. Krauss: "The Relationship of Microstructure to Fracture Morphology and Toughness of Hardened Hypereutectoid Steels," presented in Symposium Microstructural and Residual Stress Effects on the Properties of Case Hardened Steels, Atlanta, Georgia, March 9, 1983. To be published in book: Case Hardened Steels: Microstructural and Residual Stress Effects, TMS-AIME, Warrendale, Pa., April 1984.
8. T. Ando and G. Krauss: "Growth of Grain Boundary Cementite Allotriomorphs in Ternary Fe-C-Cr Alloys," in Solid-Solid Phase Transformations, edited by H. I. Aaronson, et.al., TMS-AIME, 1982, pp. 573-577.
9. C. B. Ma, T. Ando, D. L. Williamson and G. Krauss: "Chi-Carbide in Tempered High Carbon Martensite," *Metallurgical Transactions A*, Vol. 14A, June 1983, pp. 1033-1045.
10. T. Ando and G. Krauss: "Development and Application of Growth Models for Grain Boundary Allotriomorphs of a Stoichiometric Compound in Ternary Systems," *Metallurgical Transactions A*, Vol. 14A, July 1983, pp. 1261-1269.

11. F. S. Shen, E. L. Brown and G. Krauss, "The Contribution of Physical Metallurgy to Heat Treatment Practice," in Proceedings of Third International Congress on Heat Treatment of Materials, Shanghai, November 1983, pp. 2.91-2.100.
12. G. Krauss: "Tempering and Structural Change in Ferrous Alloys," for publication in Proceedings of Symposium Phase Transformations in Ferrous Alloys, Philadelphia, September 1983, TMS-AIME.

D. List of Participating Scientific Personnel

1. George Krauss: Principal Investigator
2. Elliot L. Brown: Research Associate
3. Deborah L. Yaney: Research Assistant. Received M.S. in Metallurgical Engineering, May 1981.
4. Teiichi Ando: Research Assistant. Received Ph.D. in Metallurgy, December 1982.
5. Kenneth R. Hayes: Research Assistant. Will complete requirements for M.S. in Metallurgical Engineering in July 1984.

